National Aeronautics and
Space Administration
Glenn Research Center

Power & On-Board Propulsion Technology Division

Technology Development for a Stirling Radioisotope Power System for Deep Space Missions

by

Lanny G. Thieme
NASA Glenn Research Center at Lewis Field

and

Songgang Qiu and Maurice A. White
Stirling Technology Company

National Aeronautics and
Space Administration
Glenn Research Center

Outline

- **Background**
- **Synchronized Operation of Opposed Stirling Converters**
- **Adaptive Vibration Reduction System**
- **Friction Factor for High-Porosity Regenerators**
- **NASA Glenn Supporting Technology Project**
- **Summary**

National Aeronautics and
Space Administration
Glenn Research Center

Power & On-Board Propulsion Technology Division

Stirling Radioisotope Power System

- **High-efficiency power source to provide spacecraft on-board electric power for NASA deep space missions**

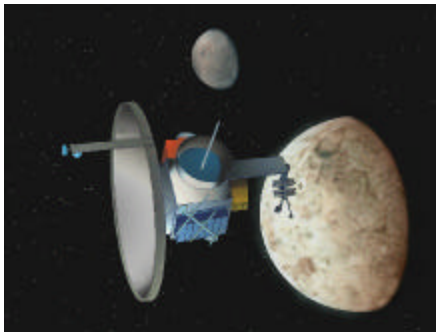
- **> 20% efficiency reduces isotope inventory by factor of 3 compared to RTGs**

  Reduces cost, mass, and radiological hazard

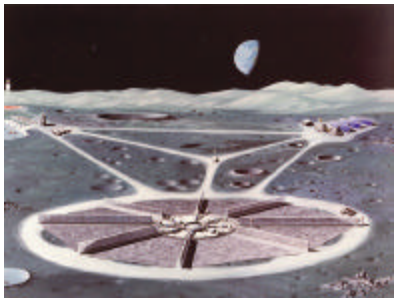
- **Stirling is most developed converter option of advanced power concepts under consideration**

- **Other Stirling space applications:**

  - Venus power and cooling
  - Lunar/Mars bases - power and cryogenic cooling
  - Planetary rovers and weather stations
  - Solar dynamic power
  - Cryocoolers for sensors



Deep space power



Lunar base

National Aeronautics and
Space Administration
Glenn Research Center

Power & On-Board Propulsion Technology Division

Stirling Radioisotope Power System

Approach

- **DOE is developing Stirling prototype converter with STC**
- **NASA Phase II SBIR developed synchronous connection for thermodynamically-independent converters**
- **NASA Phase II SBIR developing Adaptive Vibration Reduction System to eliminate vibrations over mission life**
- **NASA Glenn supporting technology for converter, components, and materials testing**

National Aeronautics and
Space Administration

Department of Energy

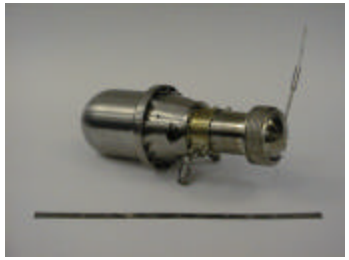
Stirling Technology Company

National Aeronautics and
Space Administration
Glenn Research Center

DOE/STC Stirling Prototype Converter

Power & On-Board Propulsion Technology Division

- **DOE/STC developing 55-We prototype converter for Stirling radioisotope power system**
  - NASA Glenn provides technical consulting under IAA



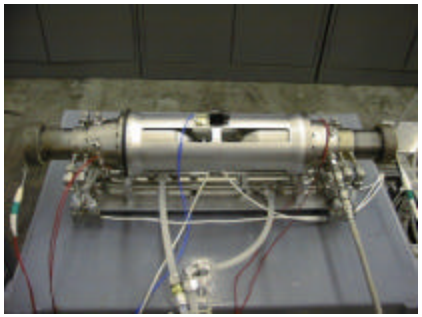
Overall size: 10" L x 3.3" Dia
Projected flight weight: 1.7 kg
Design life: 100,000+ hrs.

DOE/STC prototype converter

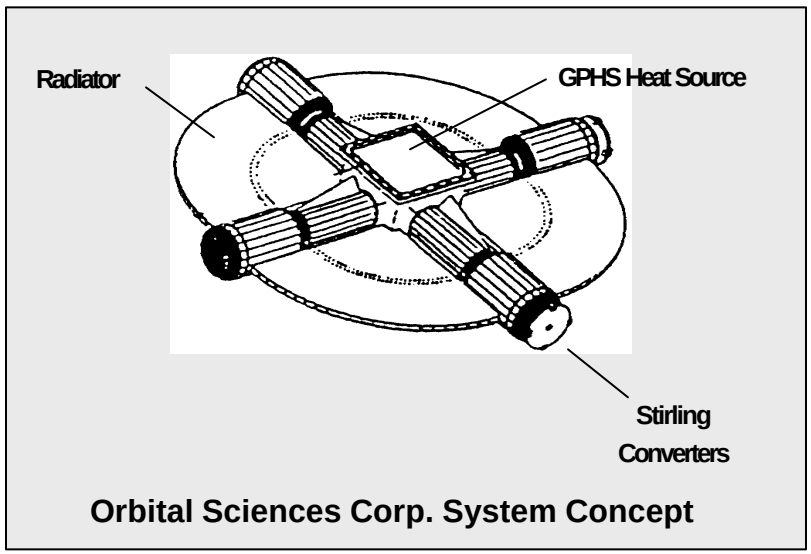
- **Design & fab completed**

  Full power achieved in June 1999

  Early efficiency indications are close to expected



Two opposed 55-We prototype converters on test



Orbital Sciences Corp. System Concept

- **DOE system studies being performed by Orbital Sciences and Lockheed Martin**
  - Both two and four converter systems under study

National Aeronautics and
Space Administration
Glenn Research Center

STC Basis for Prototype Converter

- **55-We prototype converter based on successful STC RG-10 and RG-350 developments**

- **On-going life tests:**

  10-We RG-10 — 50,600+ hrs. (5.7+ yrs.)
  No maintenance & no degradation in performance

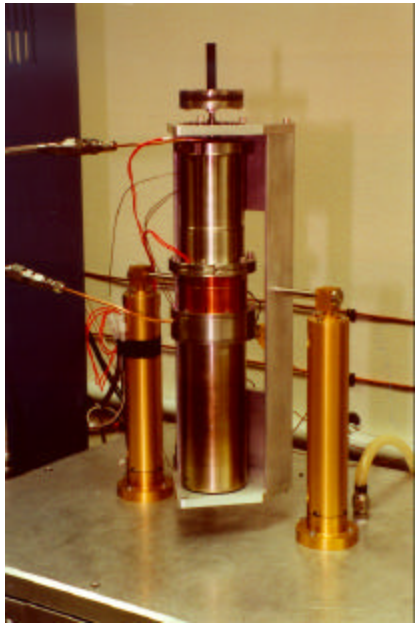
  Total flexure testing (230 flexures) — 1000+ yrs.

- **RG-10s to be field tested with isotope soon**

  RG-10s have been shock & vibration tested at DOE facilities, with engine operating

- **Common technologies between space power converter and STC commercial products**

  - BeCOOL Coolers & RemoteGen power generators
  - Beta sales underway for each
  - 80,000+ hrs. on RG-350 total family of machines



10-We RG-10 prototype

350-We RG-350 remote power generator set

National Aeronautics and
Space Administration
Glenn Research Center

Power & On-Board Propulsion Technology Division

Synchronized Stirling Converters

STC Phase II SBIR

- **Successfully demonstrated synchronous operation of two opposed 350-We thermodynamically-independent Stirling converters**

  Multiple converters are critical for reliability and modularity

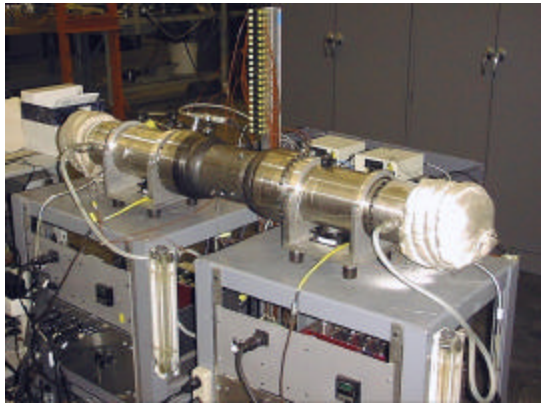
  Connection now being used for DOE/STC 55-We prototype converters

- **Parallel AC and mechanical connections**

- **Achieved synchronization over wide range of operating conditions, including simulated degradation**

  40-50 x vibration reduction relative to unbalanced converter - below pixel smear limits for deep space sensing

  Equal power generation

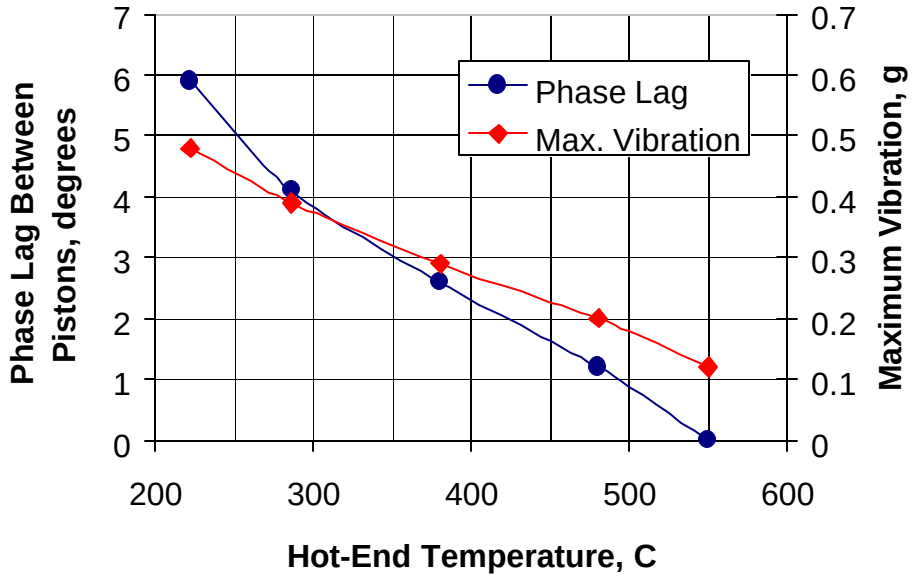


Two 350-We RG-350 synchronized converters

- **Demonstrated system operation of two converters feeding battery charger load**

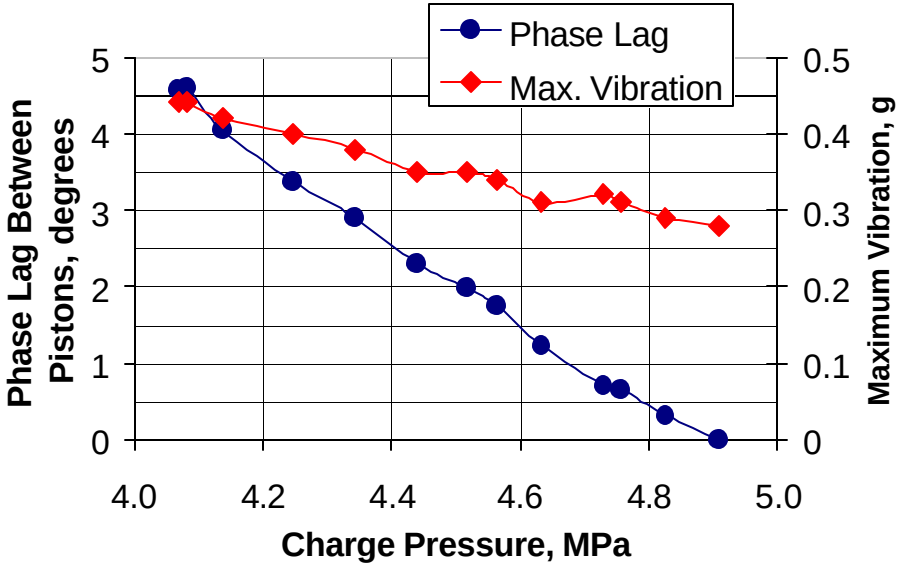
National Aeronautics and
Space Administration
Glenn Research Center

Synchronization with Simulated Degradation



- **Synchronization shown to be very robust**
  - Simulated degradation
  - Transient testing

- **Varied hot-end temperature and charge pressure in one converter over wide range**
  - **Maintained synchronization**
  - **Only slight increases in vibration**



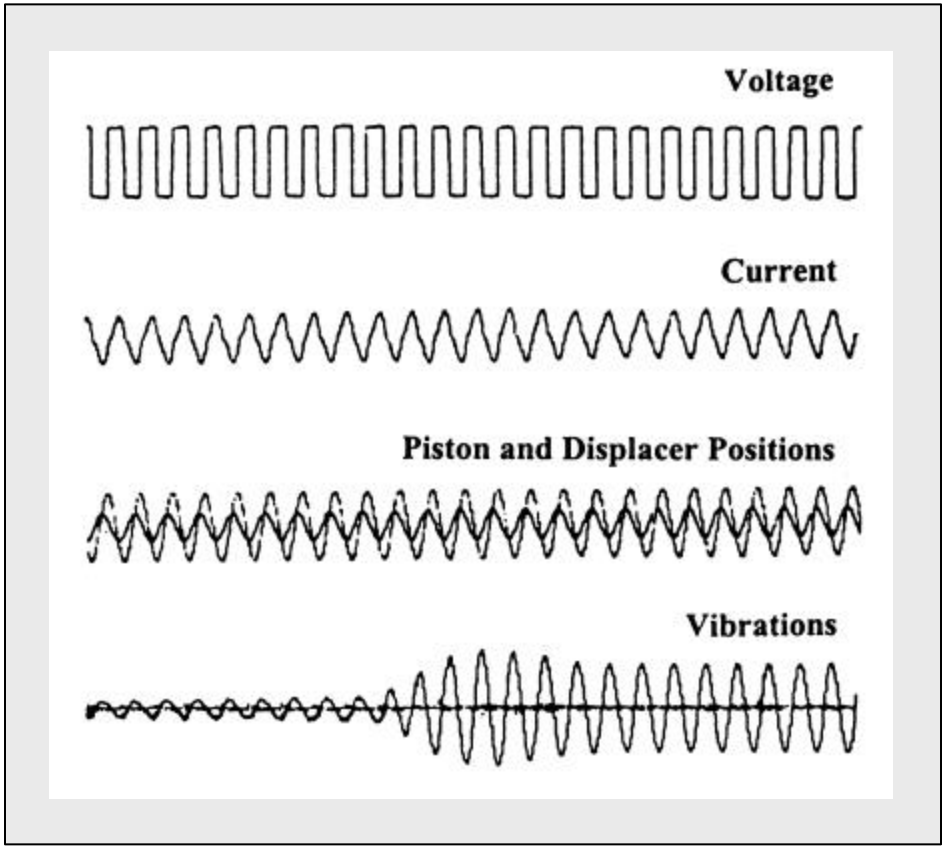
Transient Test Results

- **Various connections/disconnections showed ability to achieve synchronization rapidly and reliably**

- **No large transient overstrokes or any other potentially damaging results**

  - Only expected vibration increase when disconnect

  - Acceleration spike to 6-10 g's when connect - settles out quickly and can be mitigated if necessary



Response when parallel electrical connection is broken and one converter is shut down

National Aeronautics and
Space Administration
Glenn Research Center

Artificial Neural Network (ANN) for Health Monitoring

- **STC as part of SBIR on synchronizing Stirling converters**

- **Goal: ANN to monitor converter health using only non-invasive instrumentation**

- **Predicted piston/displacer amplitudes and phasing for RG-10 converter using voltage, current, and rejection temperature as inputs**

  Tracked simulated pressure degradation for RG-350 converter using current, current-voltage phasing, and output power as inputs

- **ANN appears to have high probability of detecting any converter degradation without needing internal instrumentation that would decrease reliability**

  - Allow controller to adjust to maximize system performance

National Aeronautics and Space Administration
Glenn Research Center

Power & On-Board Propulsion Technology Division

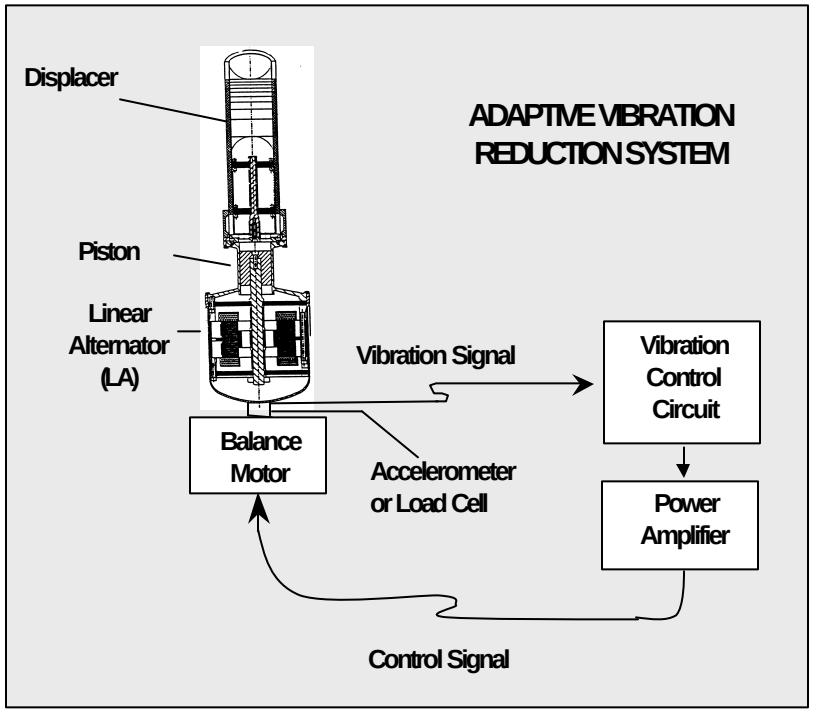
Adaptive Vibration Reduction System (AVRS)

STC Phase II SBIR

- **Key Stirling need is to eliminate vibrations over 10-15 yr. mission life**

- **AVRS will further decrease vibrations under normal operating conditions**

  And, even more importantly, adapt to changing converter conditions and any degradation or failure



- **Goal is 100 x total reduction in unbalanced vibrations under all conditions**

  - Balance fundamental and up to 10 harmonics

- **STC has demonstrated 0.007 g vibration on cryocoolers with similar techniques**

  - Varying frequency is key difference for power converters

National Aeronautics and
Space Administration
Glenn Research Center

Power & On-Board Propulsion Technology Division

Adaptive Vibration Reduction System (AVRS)

Initial Results

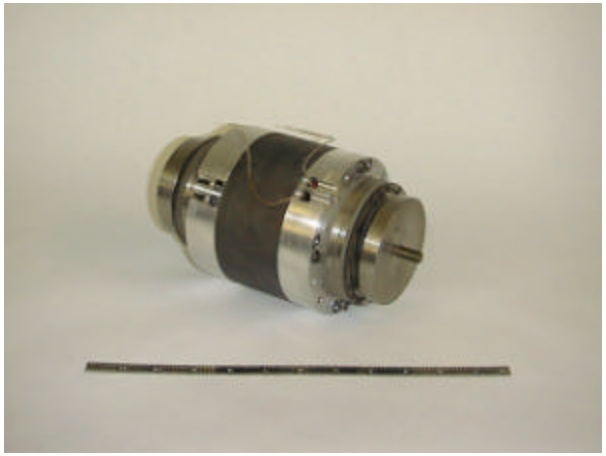
- **Initial tests of AVRS on 350-We converter have shown:**

  500 x total vibration reduction under normal conditions with only 2 W of power dissipation

  50 x vibration reduction with simulated failed converter and only 7 W of power dissipation

- **These tests only balanced fundamental and used simple algorithm**

- **Final demonstration of AVRS will be on 55-We prototype converters**



AVRS balance motor

(need 1 motor per 2 converters)

National Aeronautics and
Space Administration
Glenn Research Center

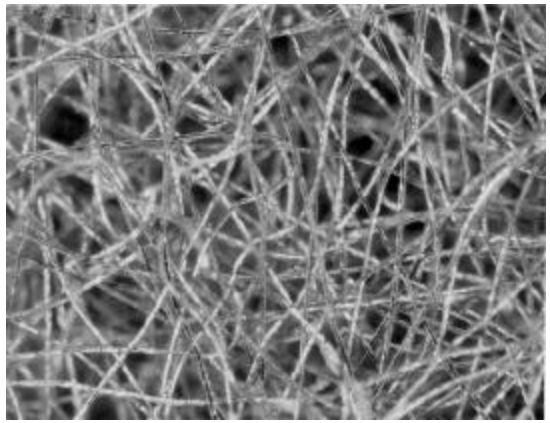
Friction Factor for High-Porosity Random Fiber Regenerators

Power & On-Board Propulsion Technology Division

- **GLIMPS, HFAST comparisons for 55-We converter design showed large differences in regenerator pressure drop loss**

  - f correlations significantly different at 90-96% porosities

- **Correlations based on test data for maximum porosities of about 84%**



96% porosity random fiber regenerator

- **STC fabricated 80, 88, and 96% porosity regenerator samples**

  - 22 micron wire diameter

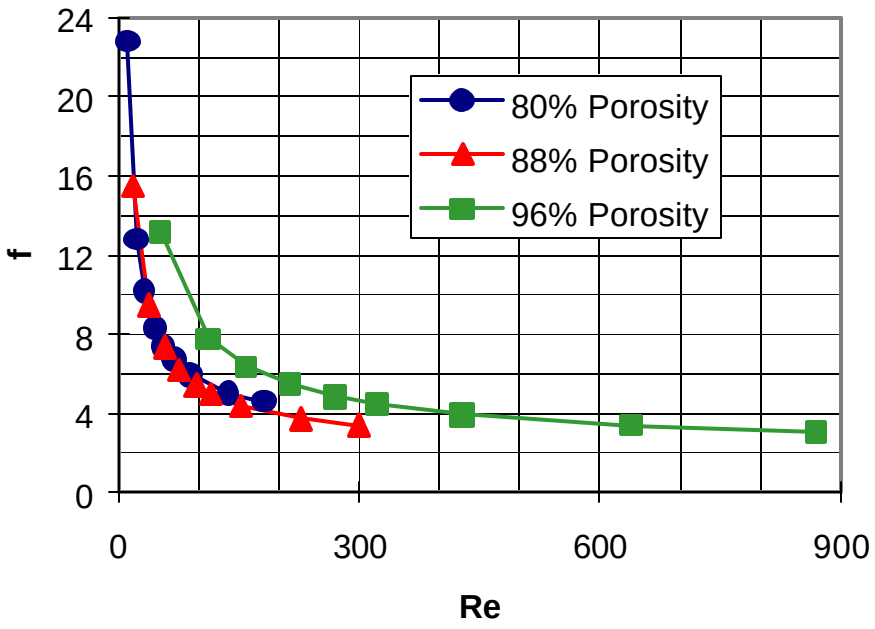
Tested in Flow Calibration Lab at NASA Glenn

- Air at 55 and 100 psia inlet pressures

National Aeronautics and
Space Administration
Glenn Research Center

Power & On-Board
Propulsion Technology
Division

Friction Factor for High-Porosity Random Fiber Regenerators



Friction factor
vs.
Reynolds number

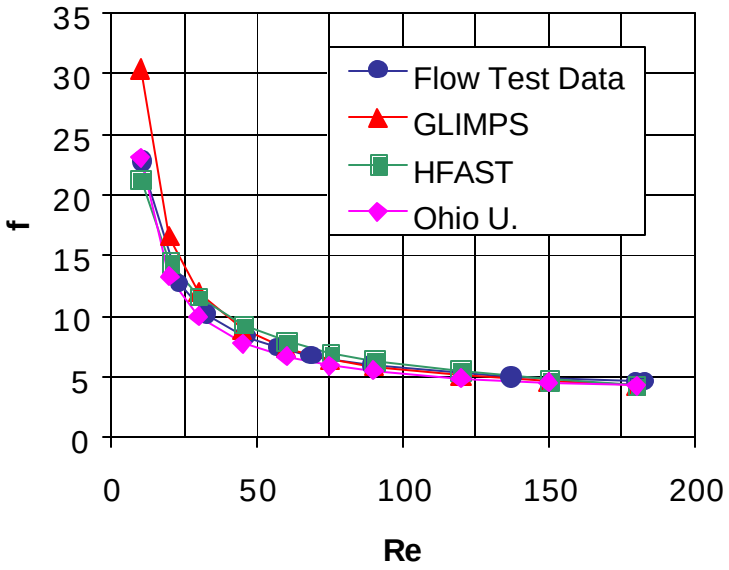
- **Good agreement between 80% and 88% samples; friction factor significantly higher for 96% sample**

National Aeronautics and
Space Administration
Glenn Research Center

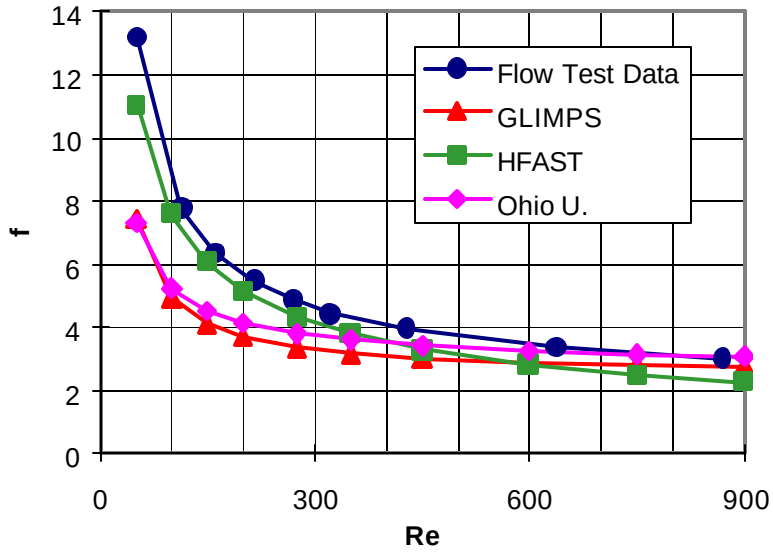
Power & On-Board Propulsion Technology Division

Friction Factor for High-Porosity Random Fiber Regenerators

80% Porosity



96% Porosity



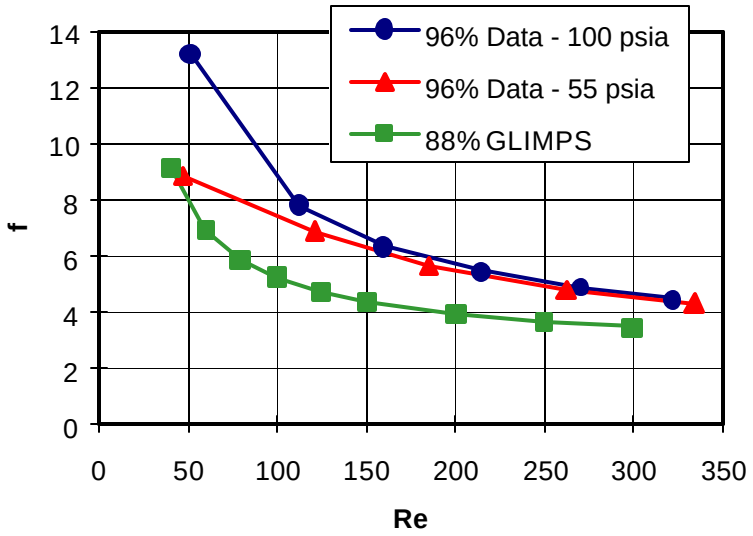
Comparisons with GLIMPS, HFAST, and recent Ohio University correlations

National Aeronautics and
Space Administration
Glenn Research Center

Power & On-Board
Propulsion Technology
Division

Friction Factor for High-Porosity Random Fiber Regenerators

- **STC derived relationship for porosities from 88-96%**
- **Final optimized regenerator design porosity was reduced from 96% to 90%**
  - **90% porosity used in 55-We prototype converter**



Inputs for STC relationship for 88-96% porosities

- **No adjustments made for heat transfer - NASA Glenn now setting up heat transfer test rig**

National Aeronautics and
Space Administration
Glenn Research Center

NASA Glenn Supporting Technology Project

Power & On-Board Propulsion Technology Division

- **Support overall development of Stirling radioisotope power system for deep space missions**

  - DOE, NASA Glenn, STC

  Build on NASA Glenn expertise developed as part of previous Stirling research, especially for SP-100 space power

- **Provide NASA Glenn tasks to develop converter for readiness for space qualification and mission implementation (TRL 6)**

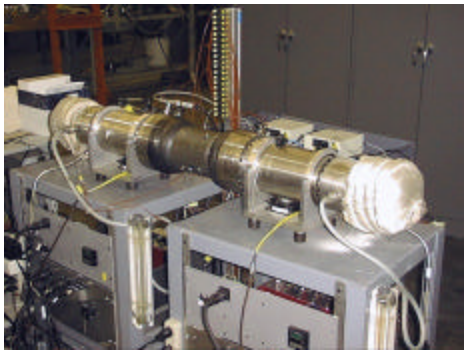
  - DOE/STC to incorporate technologies into flight prototype converter

- **Tasks:**

  - **Controls development**

    - Two 350-We and two 55-We converters as test beds

  Performance verification of 55-We converters



Synchronized 350-We converters

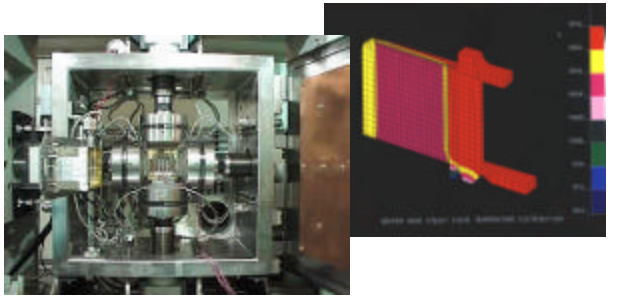
National Aeronautics and
Space Administration
Glenn Research Center

NASA Glenn Supporting Technology Project

Power & On-Board Propulsion Technology Division

- **Tasks (cont.):**
  - **Structural life assessment of Stirling heater head**

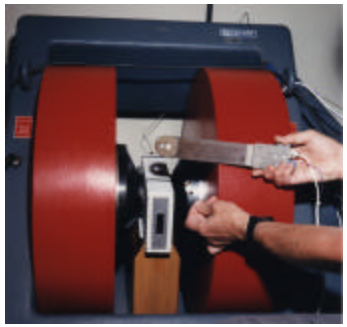
    Materials/joining evaluations



Heater head life assessment

  - **Magnet screening and thermal aging tests**
    - FeNdB and SmCo magnets

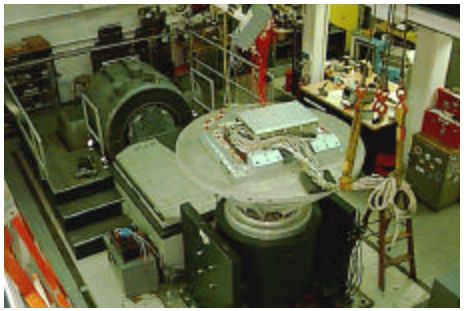
    Alternator FEA analysis



Magnet characterization test rig

  - **Demonstrate converter operation under launch and orbit transfer load conditions**

  - **Radiator conceptual design**
    - Initial screening studies for heat pipe and non-heat pipe concepts done for DOE



Vibration lab test facility

National Aeronautics and
Space Administration
Glenn Research Center

Summary

- **NASA Glenn, DOE, and STC are developing Stirling converter for radioisotope power system to provide on-board power for NASA deep space missions**

  - Alternative to replace RTGs with high-efficiency power source

- **STC is making rapid progress in developing and demonstrating 55-We converter**

  - Achieved full electric power output
  - Early efficiency indications are close to expected

  Numerous test hours on various systems and components provide high confidence in meeting life and reliability goals

- **Developing key converter technologies under NASA SBIRs**

  - Vibration levels demonstrated more than order of magnitude below pixel smear limits

  Orbital Sciences and Lockheed Martin evaluating system designs

- **Now initiating NASA Glenn supporting technology project to assist in developing converter for readiness for space qualification and mission implementation**